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THE QUANTITATIVE ANALYSIS OF FATIGUE CRACKING UNDER PROGRAMMED --ETC(U)
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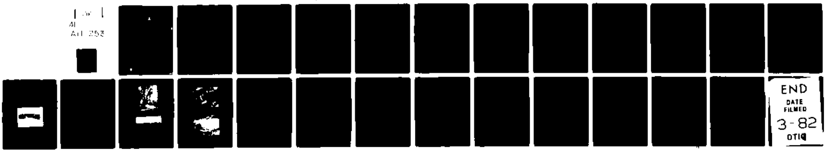

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by

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Farnborough, Hants

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SUMMARY

Premature failure of an undercarriage cylinder occurred during a fatigue test in which programmes of severe and standard loading cycles had been applied representing severe and standard ground handling conditions. Fatigue crack growth rates were predicted using a fracture mechanics rationale based upon a modified version of the Forman law for fatigue crack growth. The predicted rates agreed, to within ±30%, with the rates measured as the spacings of fatigue striations on the fracture surface and a predicted total life agreed with the actual fatigue life to within 10%. This indicated that the undercarriage loadings had been applied correctly and that errors in the loading were not the cause of the premature failure.

It was found that the fatigue cracks initiated at a change in section with a poorly machined finish. A fracture mechanics analysis of the striation spacing growth rates close to the change in section indicated that the rough machining effectively increased the k_t of the change in section from 1.7 to nearly 5, producing premature crack initiation and a short fatigue life.

The predicted growth rates were found to vary significantly from those measured after a beneficial reduction in duty cycle severity, such beneficial load interactions effects being beyond the scope of the prediction model.

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1 INTRODUCTION

It is accepted that fatigue cracks will initiate and grow in the structures of virtually all military and civil aircraft during some period of their service lives. This tenet is part of the basis of the damage tolerant design philosophy[1]. It is essential that the growth of these cracks be predicted accurately and this requires a knowledge of the location of likely initiation sites in the structure and of the subsequent rates of crack growth. Design studies yield valuable information on the fatigue sensitive areas of an aircraft structure but must be supplemented by the fatigue testing of major components of the structure. This Report compares rates of fatigue crack growth predicted from a knowledge of the fatigue loadings, essentially a design study, with those measured on the fractured surface of an undercarriage component broken during fatigue testing. The results produce evidence of load interaction effects, which are often not considered in design studies, and of the powerful effects of surface finish on crack initiation.

This Report develops the method, outlined previously[2], for the prediction of crack growth rates under programmed loading by including the effects of variable fatigue mean stresses and the fracture toughness of the material. Once again crack growth rates are measured fractographically as the spacings of fatigue striations on the fracture surface. A further report in preparation compares a similar prediction of crack growth rates with those observed fractographically on an in-service failure.

2 THE UNDERCARRIAGE TEST

The undercarriage main fitting failed prematurely during testing, that is after approximately one tenth of its designed fatigue life had been achieved. Failure occurred by the growth of a transverse fatigue crack at a change in section in the undercarriage cylinder wall. The crack penetrated the cylinder wall, jumped forward abruptly for several millimetres, stabilized and, after a further small period of stable fatigue crack growth, catastrophic failure occurred (Figs 1 and 2). The undercarriage had been loaded servo-hydraulically to represent the vertical, drag and side loads experienced in service. The combination of these different types of loadings produced a duty cycle of fluctuating tension stresses representing the stresses set up during one aircraft flight, *ie* taxying, engine run-up, take-off and landing and finally braking.

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The duty cycle illustrated (Fig 3) represented loadings applied to represent a standard landing. Additionally the braking, taxying, turning and engine

run-up components were increased in magnitude to represent severe ground handling conditions. This was achieved by increasing both maximum and minimum stress levels of the appropriate components of the duty cycle by approximately 11%. The standard and severe duty cycles were applied in blocks during fatigue testing:-

9000 duty cycles of standard landings
1650 duty cycles of severe landings
3459 duty cycles of standard landings

to give a total of 14109 duty cycles at failure.

3 FRACTOGRAPHIC EXAMINATION

Several fatigue cracks were found to have initiated, and to have grown and combined into the semi-elliptical crack observed (Fig 2). The crack origins were all located at the root of the change in section and were associated with coarse machining marks (Figs 4 and 5). There was no evidence of any metallurgical defects at the fatigue crack origins.

High magnification fractography revealed numerous fatigue striations in definite bands on the fracture surface. These striations were visible over a considerable portion of the fatigue fracture surface and were similar in appearance at both short and long crack depths (Figs 6 and 7) albeit of greater spacing at the greater depths. The spacings of the striations were readily measured as a function of crack depth (Fig 8). Detail within the striation bands indicated that each band was formed by crack growth under a complete duty cycle of loadings and growth rates were plotted as crack extension per duty cycle (Fig 8). Abrupt changes in crack growth rate were observed at 4 mm crack depth and, less obviously, at 0.5 mm crack depth. The early stages of crack growth were replotted for greater clarity (Fig 9). These abrupt changes in growth rate were attributed to deliberate changes in loading severity during the test, that is from standard duty cycles to severe duty cycles and back. The number of duty cycles between the two changes in growth rate was calculated by integration of reciprocal growth rates and found to be approximately 1800 duty cycles. This was in reasonable agreement with the 1650 severe duty cycles that were known to have been applied. The total number of duty cycles from an initiation or incubation crack depth of 0.125 mm to penetration of the cylinder wall was calculated to have been approximately 4400 duty cycles comprised of 1030 standard duty cycles from initiation at 0.125 mm to 0.5 mm, 1800 severe duty cycles from 0.5 mm to 4.0 mm and 1580 standard duty cycles from 4.0 mm to the inner wall at a depth of 8.0 mm. Striation data for the subsequent crack growth around the cylinder was not obtained.

4 THE PREDICTION OF FATIGUE CRACK GROWTH RATES

Fatigue crack growth rates were predicted for the undercarriage cylinder using laboratory data and the levels of applied stresses in order to check that the actual growth rates had been consistent with the nominal applied stresses. Each stress cycle in the duty cycle (Fig 3) was assumed to contribute to the total crack growth rate. It was assumed that the size of each contribution would not depend upon previous load cycles, *ie* that there had been no interactions between successive high and low amplitude cycles.

The prediction was based upon a modification[3] of the Forman[4] crack growth law, where the rate of growth per cycle da/dn, is related to the range in stress intensity factor ΔK, the ratio R of minimum to maximum stress in each fatigue cycle and the fracture toughness K_c :-

$$\frac{da}{dn} = \frac{C\Delta K^m}{\left[(1 - R)K_c - \Delta K\right]^{\frac{1}{2}}} \quad . \qquad (1)$$

The constants m and C were determined from a plot of $\log \frac{da}{dn}\left[(1 - R)K_c - \Delta K\right]^{\frac{1}{2}}$ versus $\log \Delta K$ for the undercarriage alloy 7050 T736 (Fig 10). Unfortunately the data[5,6] for 7050 forgings was very limited and has had to be supplemented by that for 7079 forgings since the lack of data for 7050 at high values of ΔK produced a slightly higher value for m than normal[3]. The value of C for 7050 was found to be approximately half that for 7079 and a value of 44 $MPa\sqrt{m}$ was chosen for K_c .

Equation (1) requires a value of ΔK which was a function of crack depth and component geometry. For convenience all the geometrical factors affecting ΔK were combined in the term Z :-

$$\Delta K = Z\Delta\sigma \quad . \qquad (2)$$

An exact value for Z was required for the range of crack depth from the surface through the cylinder wall and then around the cylinder wall to final failure. Z depended upon the surface elastic stress concentration k_t , the crack front shape expressed as the integral for a semi-elliptical crack front ϕ and upon correction factors for the inner and outer surfaces of the cylinder wall, 1.12 and K_I/K_0 respectively:-

$$Z = 1.12k_t \frac{K_1}{K_0} \frac{\sqrt{\pi a}}{\phi} . \tag{3}$$

The values of K_1/K_0 and ϕ must have varied as the crack grew and it seemed likely that the effects of the stress concentration factor (k_t) associated with surface curvature and with machining damage would diminish as the cracks grew into the section. The situation was simplified by considering two limiting cases. Firstly, for very shallow cracks ($a \ngtr 1.0$ mm):-

$$Z = \frac{1.12k_t\sqrt{\pi a}}{\phi} \tag{4}$$

the effects of the presence of the inner cylinder wall represented by K_1/K_0 were neglected and the effects of k_t were assumed to be constant. Secondly, for deep cracks ($a > 6$ mm):-

$$Z = 1.12 \frac{K_1}{K_0} \frac{\sqrt{\pi a}}{\phi} \tag{5}$$

the effects of k_t were assumed to have diminished but a back surface correction K_1/K_0 was now required. This was small $[(K_1/K_0) < 1.1]$ because, even when the crack penetrated the cylinder wall it must have behaved as a small central crack in a large plate and K_1/K_0 was consequently assumed to be unity. Once the crack had penetrated the cylinder wall, the crack depth was described by the half crack length, c, at the surface rather than the depth from the surface.

$$Z = \frac{K_1}{K_0} \frac{\sqrt{\pi c}}{\phi} . \tag{6}$$

Equations (4) and (5) provided limiting values for Z and, at intermediate crack depths (1 mm $< a <$ 5 mm), a more realistic value was assumed to be given by considering an effective k_{t_e} which diminished, as the crack grew, in proportion to the assumed[7] diminution in elastic stresses developed near an elastic stress concentration:-

$$Z = 1.12k_{t_e} \frac{\sqrt{\pi a}}{\phi} . \tag{7}$$

The selected solutions for Z were plotted as a function of crack depth (Fig 11) using a value of ϕ determined from the apparent crack front shape. The crack was assumed to be semi-elliptical at short depths with a c:a ratio of 2:1 ($\phi = 1.2$) and with penetration of the cylinder wall to increase in curvature to semi-circular at final failure ($\phi = 1.57$). An abrupt increase in curvature had occurred at 18 mm depth where the crack had jumped. A smooth curve, representing the best estimate for Z compounded from the selected solution, was drawn and used for the growth rate predictions (Fig 11). Combining equations (1) and (2):-

$$\frac{da}{dn} = \frac{C(\Delta\sigma Z)^m}{[(1 - R)K_c - Z\Delta\sigma]^{\frac{1}{2}}} \quad . \tag{8}$$

Each component of the duty cycle, with its characteristic values of $\Delta\sigma$ and R, was considered. Similar components such as the six turning cycles were combined for convenience. The total rates predicted were plotted with the striation data (Figs 8 and 9) and the contributions to the total rate were plotted as a function of crack depth (Fig 12). It was found that the engine run-up cycle was the major contributor to the total growth rate, with significant further contributions from the braking and taxying loads.

Generally, the predicted growth rates matched the striation spacings very well, the predicted rates lying within the striation scatter band. However, a closer examination revealed a significant over-prediction in rate immediately after the change from severe duty cycles to standard duty cycles (Fig 8). The effect was found to persist far in excess of 1000 duty cycles until the striation spacing had increased to the predicted level at 8 mm crack depth. The deceleration in actual growth rate below that predicted was taken as evidence for a load interaction effect that persisted over a considerable distance. It should be noted that at high growth rates (> 3 μm/cycle) it was anticipated that the striation spacing would underestimate actual growth rates because of a significant contribution from crack jumping[8]. A further discrepancy was observed at very short crack depths, where the predicted rate significantly underestimated the growth rate. The most likely cause for this underestimation was thought to have been a low prediction of the value of Z at short crack depths. That is, whilst the effects of the combinations of several small cracks growing from separate origins were hard to predict, it would seem that the value of k_{t_e} was increased at the surface by the coarse machine marks. Consequently, values of Z were

calculated to give a perfect fit to the striation data and values of k_{t_e} were recalculated from the new values for Z. It was found (Fig 13) that the striation data for short cracks suggested that the surface k_{t_e} may have been as high as five but that its effects diminished very quickly as the crack grew. This appeared to indicate that the surface k_{t_e} was the product of a nominal k_t of 1.7 for the surface curvature and locally a value of approximately three for the deep machine marks. The deleterious effects of the coarse machining were thus very severe.

5 THE PREDICTION OF TOTAL FATIGUE LIFE

Fatigue striation spacings were found to be in reasonable agreement with crack growth rates predicted by fracture mechanics. Growth rates were predicted for the whole fatigue crack from initiation at 0.125 mm to catastrophic fracture of a through crack at 22 mm (Fig 14). The reciprocals of the rates were calculated and used to integrate the number of duty flights taken to grow the crack between selected crack depths:-

<table>
<tr><th>Crack depth
mm</th><th>Predicted
duty cycles</th><th>Applied
duty cycles</th></tr>
<tr><td>0-0.125</td><td>8000</td><td rowspan="2">9000</td></tr>
<tr><td>0.125-0.50</td><td>1030</td></tr>
<tr><td>0.5-4.0</td><td>1800</td><td>1650</td></tr>
<tr><td>4.0-22</td><td>2500</td><td>3450</td></tr>
<tr><td>Total</td><td>13300</td><td>14100</td></tr>
</table>

The initial period of crack growth 0-0.125 mm was treated as an initiation and incubation stage. It has been reported that for the severity of the surface stress concentration, taking into account the rough machining, this initiation period should have taken approximately 60% of the total life. Thus the 5330 duty cycles from 0.125 mm to 22 mm represented 40% of the total life and the 8000 cycles of initiation were readily calculated. It was found that the predicted life agreed well with the actual life in terms of both initiation and crack growth periods, with the exception of an underestimate of the number of duty cycles from 4 mm to 22 mm. This may have been caused by an overestimate of the exponent m in the crack growth equation or possibly by a beneficial load interaction effect not taken into account.

Conventional stress-life data was also used to predict the total fatigue life using the concept of the effective stress cycle. A simple sinusoidal stress cycle was defined having the same effect upon the rate of fatigue crack growth

as either the severe duty cycle or the standard duty cycle. A comparison of the predicted total growth rate (Fig 12) with the laboratory data (Fig 10) revealed that the effective stress cycle was approximately 1.2 times the magnitude of the large engine run-up cycle with same zero value of R. The engine run-up stress cycle had a range of 191 MPa for the severe case and 173 MPa for the standard duty case and the effective stress cycles were therefore 229 MPa and 208 MPa respectively. Stress-life data for these effective stresses were obtained by combining data for 7050-T73651 plate and 7050-T736 die forgings for a k_t of 3 (Fig 15). Lives of 8000 severe duty cycles and 10200 standard duty cycles were predicted by the plate data for the two effective stress cycles. The limited data indicated that forged material might have had a slightly longer life. The actual fatigue life was a combination of 1.21 times the predicted standard life plus 0.21 times the predicted severe life; a small underprediction in fatigue life of the order of the scatter in the laboratory data. Data for a k_t of 3 was used in the prediction but the quality of the surface finish of the laboratory test pieces was unknown.

6 DISCUSSION

The prediction of fatigue crack growth rates based upon the modified equation of Forman, was found to be in reasonable agreement with the rates measured as striation spacings, except for a significant unpredicted retardation in growth rate when the severe duty cycle was changed to the standard duty cycle. It seemed that the 11% reduction in mean load produced a long term beneficial effect. The beneficial effects of large loads upon subsequent smaller load cycles have been well reported[9,10] and the particularly beneficial effects of blocks of large load cycles upon subsequent growth under lower amplitude cycles was to be expected. The agreement between measured growth rates and predicted rates in this case suggested that interactions between individual loads in the duty cycle must have been insignificant although this may have been because the total rate predominantly comprised the rates for the two large load cycles representing engine run-up and braking (Fig 12).

For the majority of the crack growth up to 8 mm depth the predicted rates were within ±30% of the striation data, that is within the expected scatter in the striation data. The predicted total life was within 10% of the actual fatigue life, far better than had been anticipated and the results suggested
073 that, if the value of m had been further reduced from 3.46, a slightly closer prediction could have been made although such a reduction could not be justified from the laboratory data. Nevertheless, it is clear that an accurate prediction

of fatigue crack growth rates and of fatigue life is quite possible, provided that the stress distributions in the component are understood and the effects of surface finish are taken into account. Further evidence, that surface finish can significantly influence early stages of fatigue crack initiation and growth, can be found in the work[11] of Nix where the quality of finish of holed test pieces ($k_t = 3$) was varied systematically.

7 CONCLUSIONS

(1) A modified version of the Forman law for fatigue crack growth was found to predict fatigue crack growth rates in an undercarriage cylinder subjected to fatigue loadings that represented aircraft landings.

(2) The predicted growth rates were generally within ±30% of the rates determined from measurements of striation spacings and the predicted total life was within 10% o' that obtained.

(3) A significant error in the prediction of growth rates resulted from a beneficial load interaction effect caused by a change in the severity of the landing duty cycle from that representing severe ground handling conditions to that for normal ground handling conditions.

(4) Premature initiation of the fatigue cracks was directly attributed to poor surface finish of the undercarriage cylinder in the region of a change in section. The poor finish effectively raised the stress concentration k_t of the change in section from 1.7 to nearly 5.

Acknowledgments

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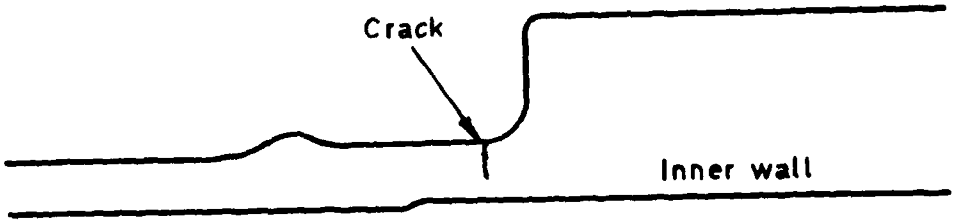

Fig 1 A longitudinal section of the undercarriage wall in the region of the fatigue crack x1

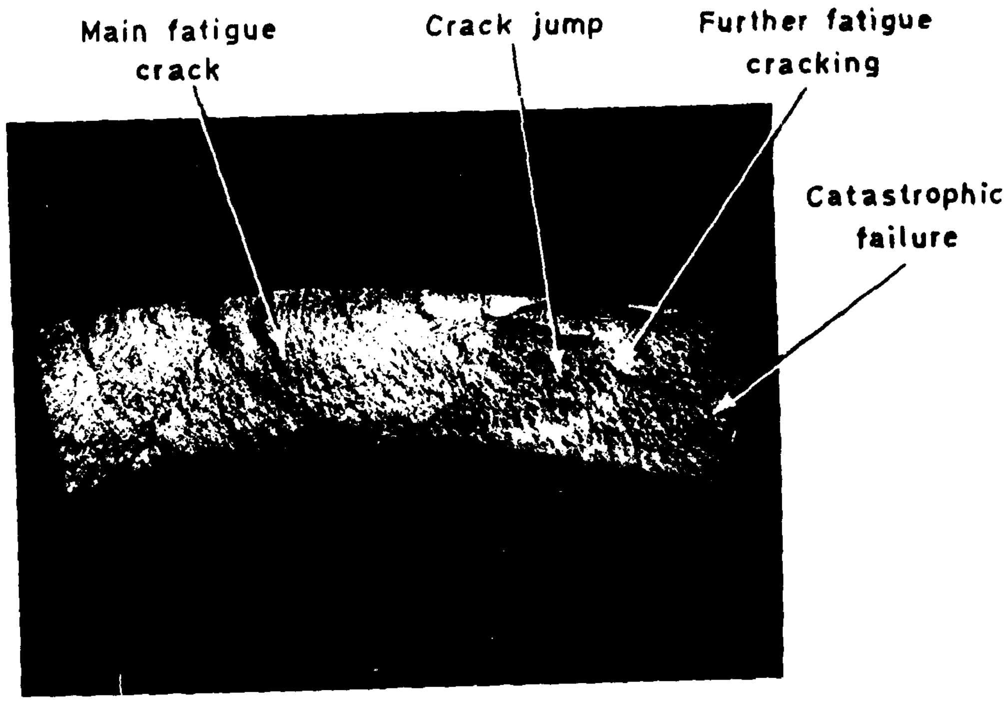

Fig 2 Half of the fracture surface showing the bright semi-elliptical fatigue crack. This is in effect a transverse section of the undercarriage wall in the plane of the crack in Fig 1 x3

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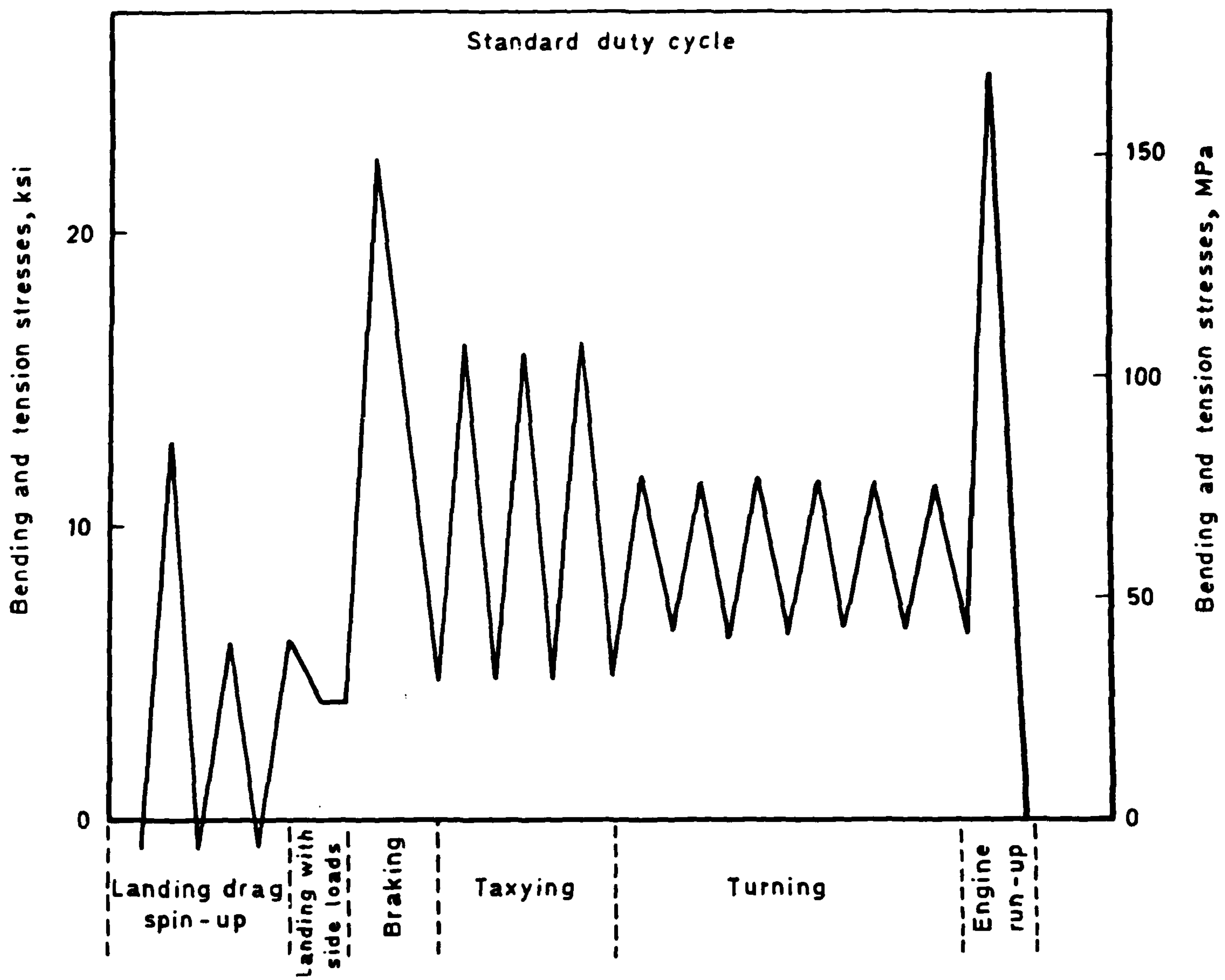

Fig 3 The standard duty cycle of loadings. Stress maxima and minima for the severe duty cycle were approximately 11% higher

Fig 4 A fatigue crack origin showing the roughly machined surface x 50

Fig 5 A micro-section of the roughly machined surface. The machining scallops are filled with anodic film x 600

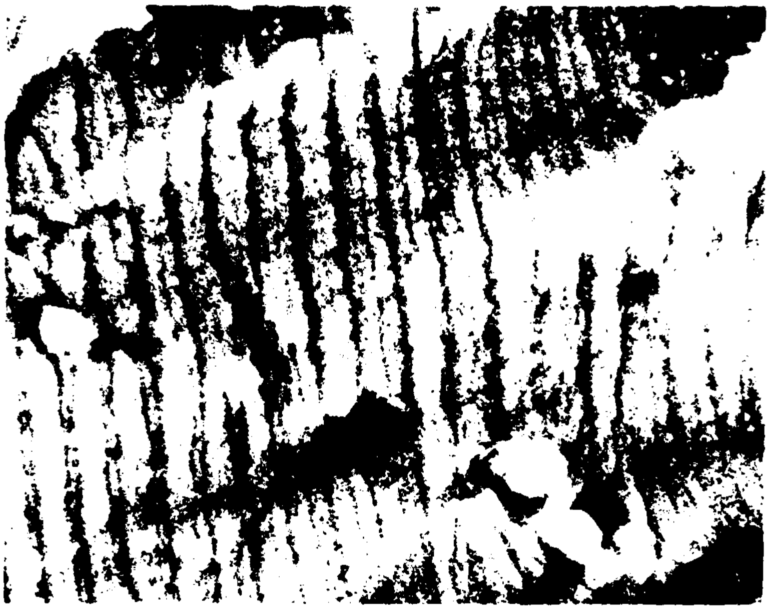

Fig 6 Fatigue striation bands at a crack depth of 0.8 mm.
Severe duty cycle x 4400

Fig 7 Fatigue striation bands at a crack depth of 7.2 mm.
Standard duty cycle x 1000

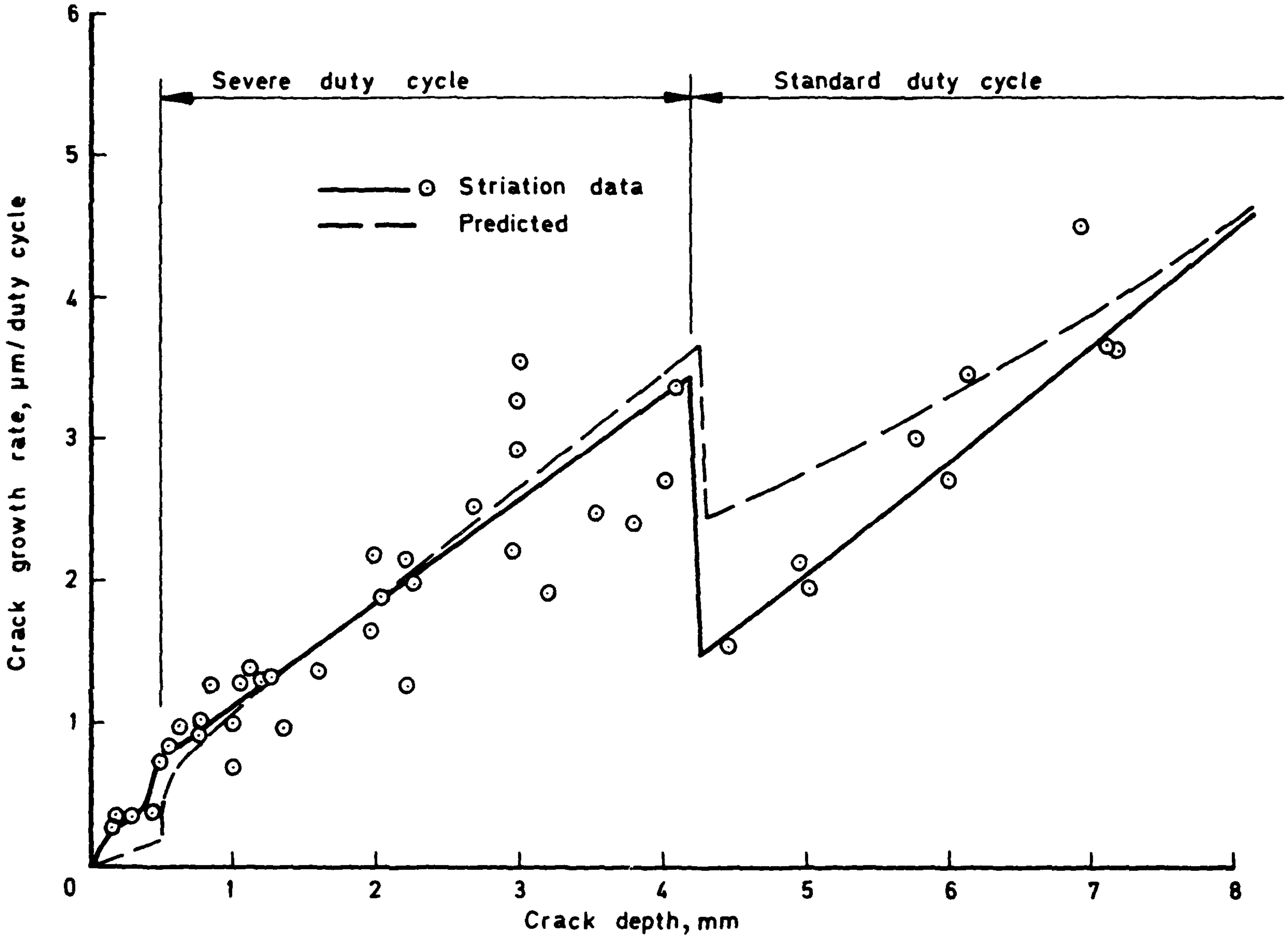

Fig 8 Predicted and measured crack growth rates

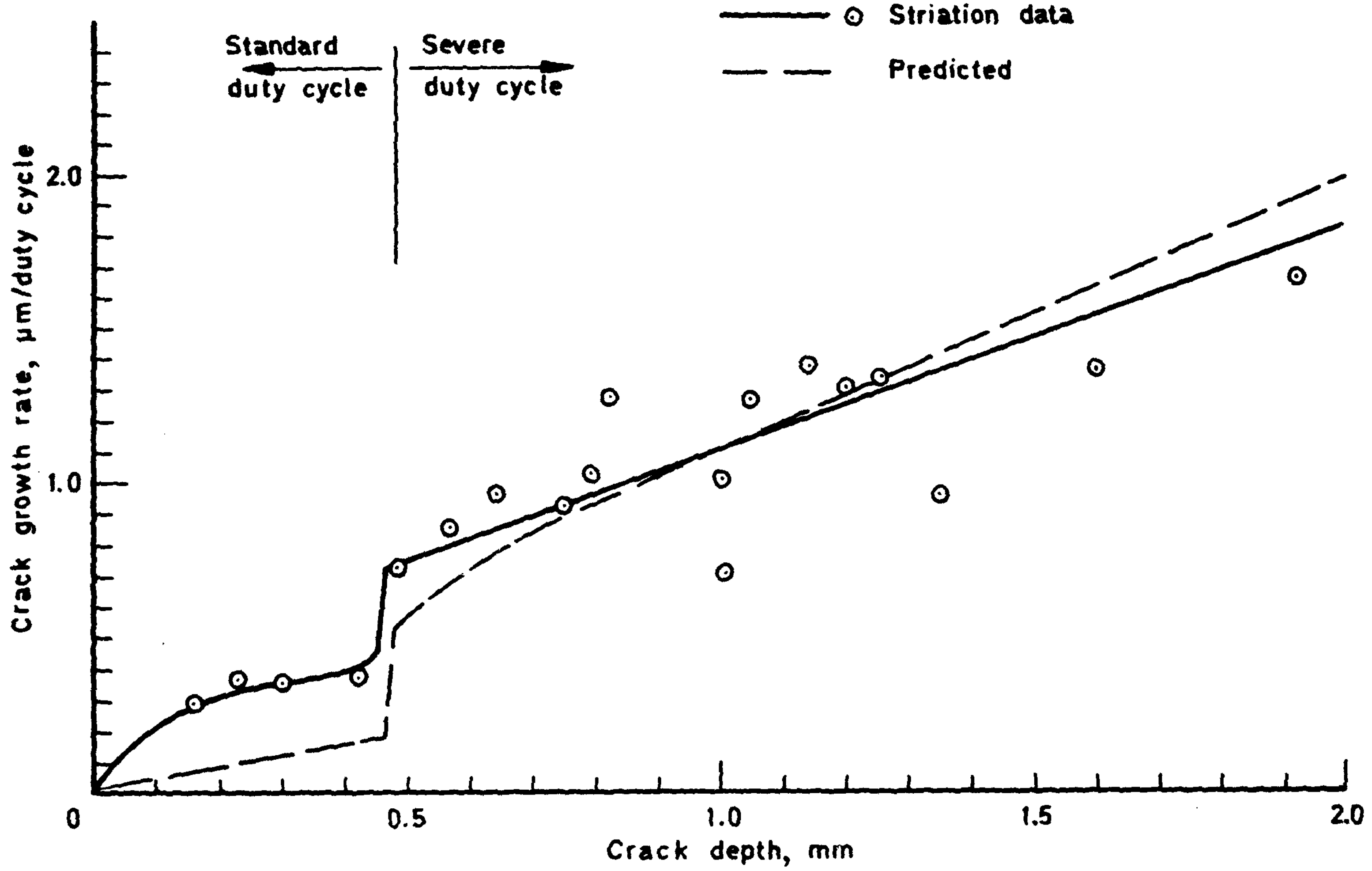

Fig 9 Predicted and measured fatigue crack growth rates at short crack depths

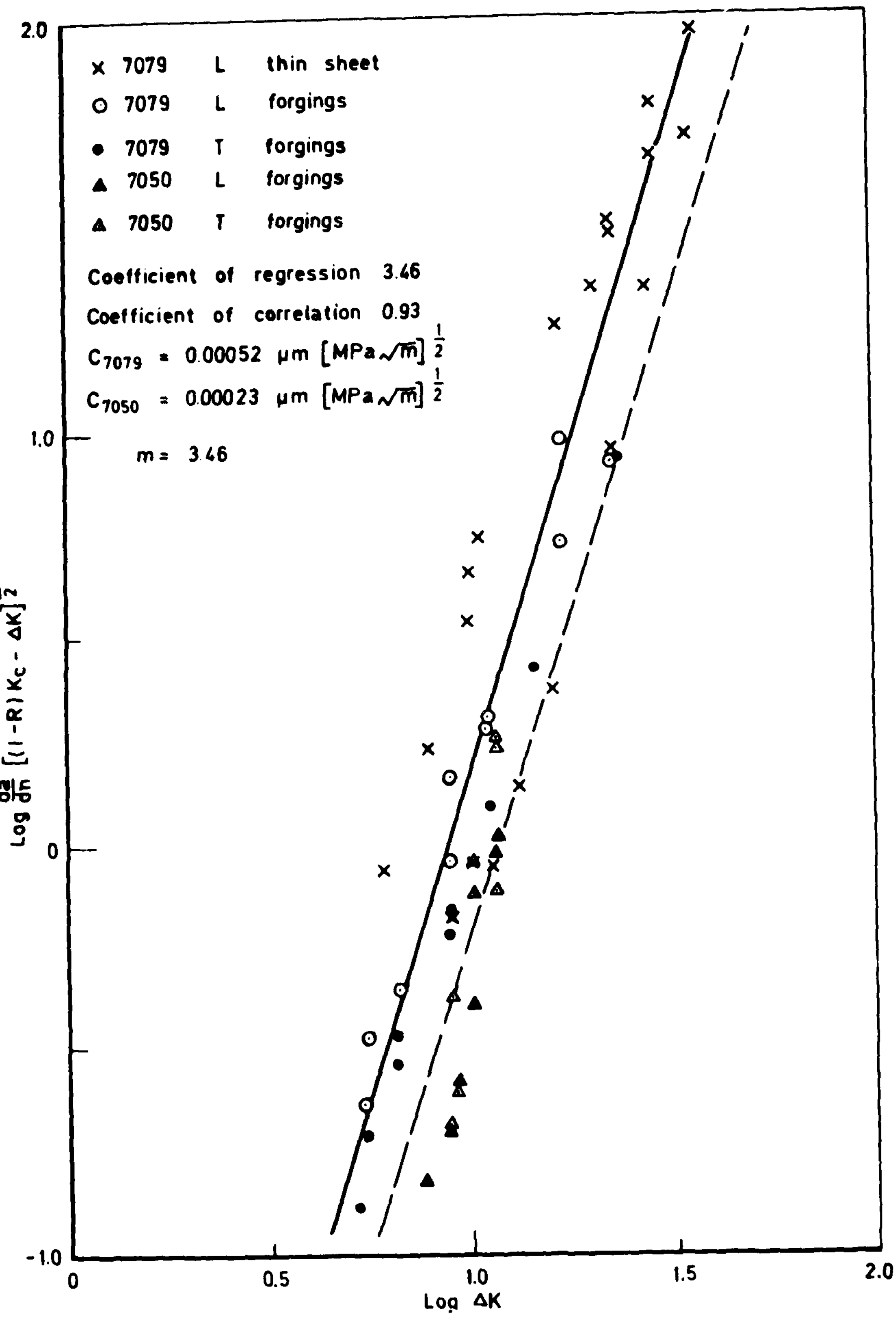

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Fig 10 Log $\frac{da}{dn}$ $[(1-R)K_c - \Delta K]^{\frac{1}{2}}$ versus log ΔK for 7079 and 7050

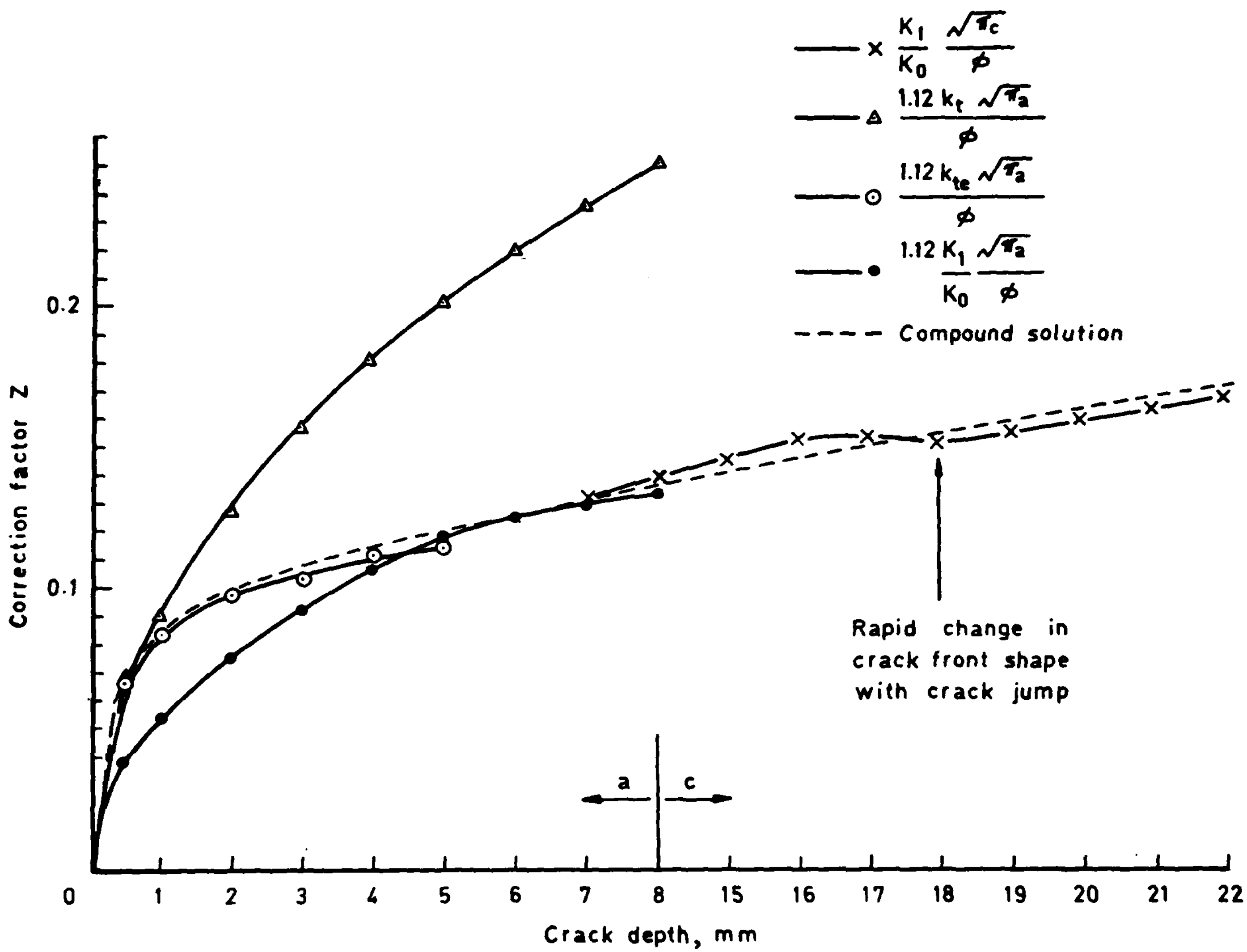

Fig 11 **Predicted values for the correction factor Z for the various solutions and the compounded solution used for growth rate predictions**

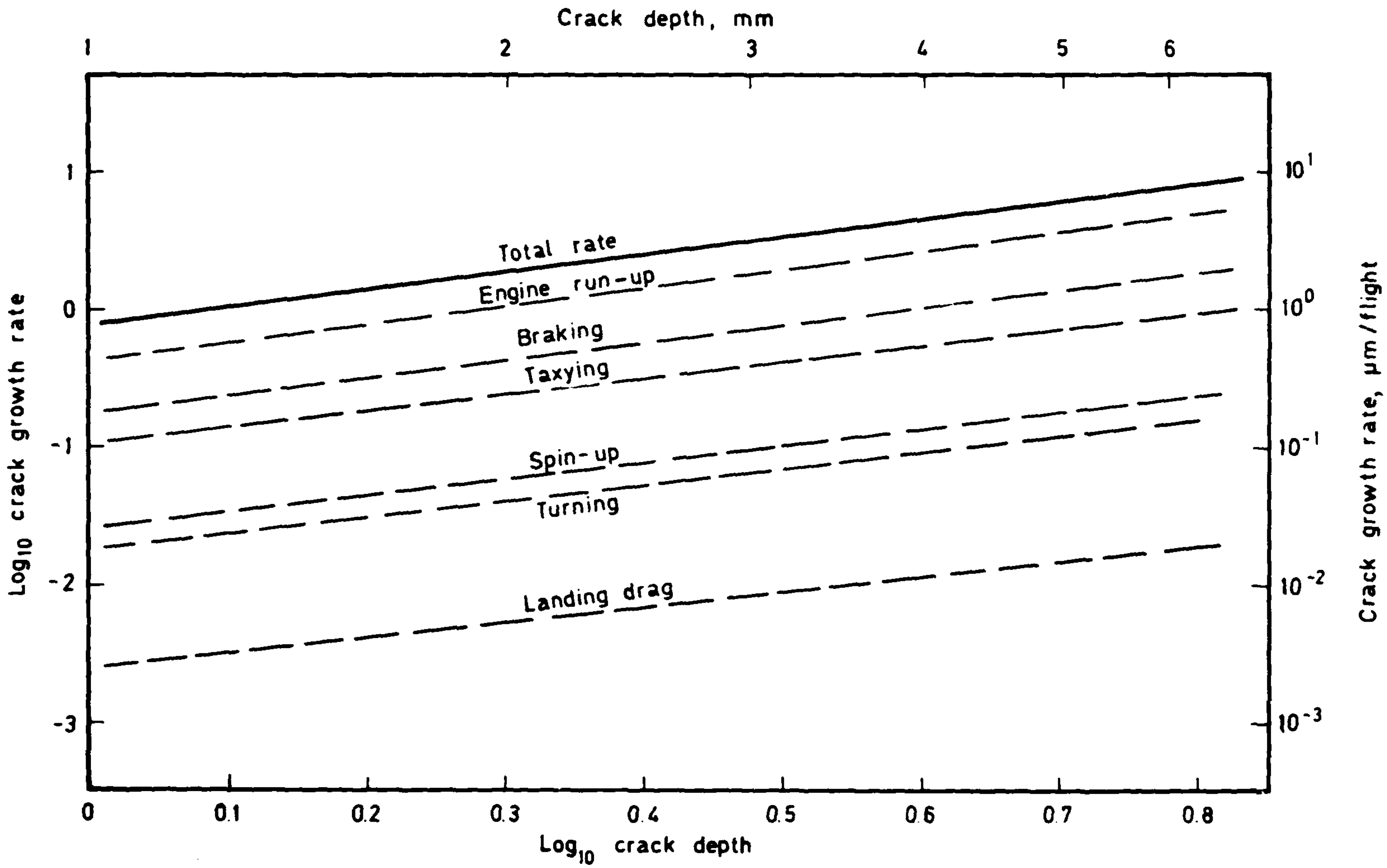

Fig 12 Predicted crack growth rates for the severe duty cycle $m = 3.46$, $c = 0.000229\ \mu m[MPa\sqrt{m}]^{1/2}$, $K_c = 44\ MPa\sqrt{m}$

Fig 13

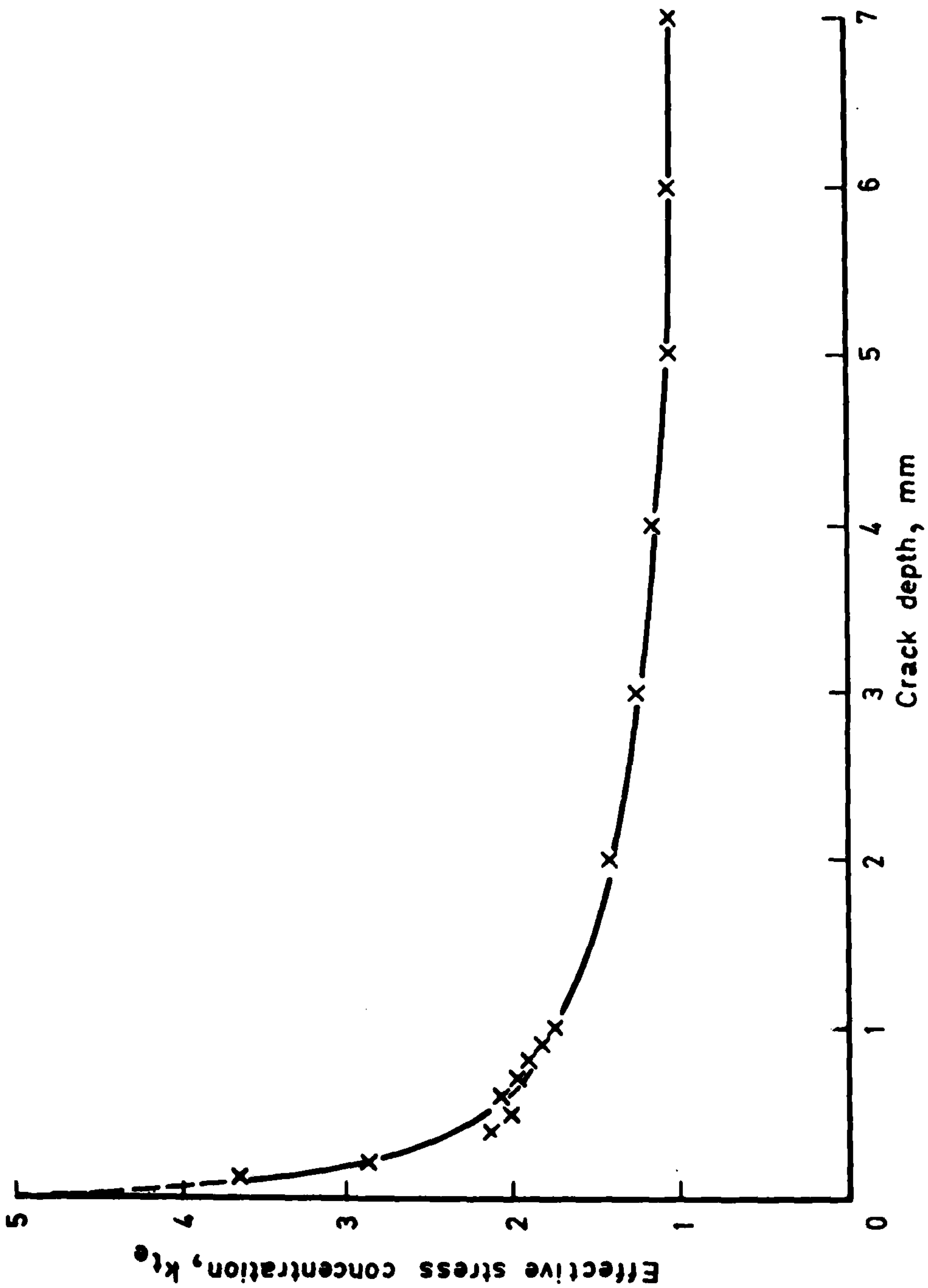

Fig 13 The apparent or effective stress concentration predicted by the striation spacings

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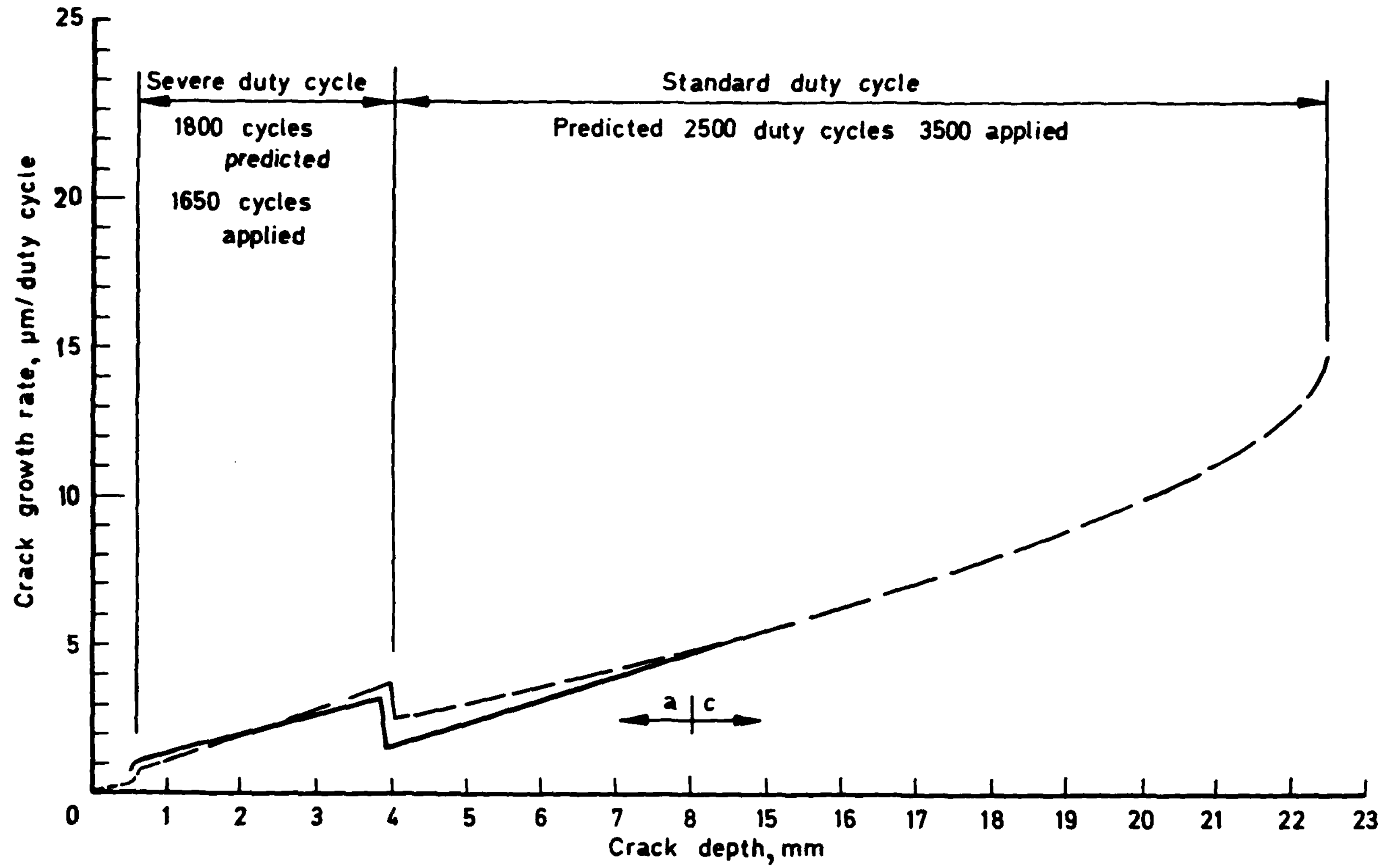

Fig 14 Fatigue crack growth rates from initiation to catastrophic failure. The crack penetrated the cylinder wall at a depth of 8 mm

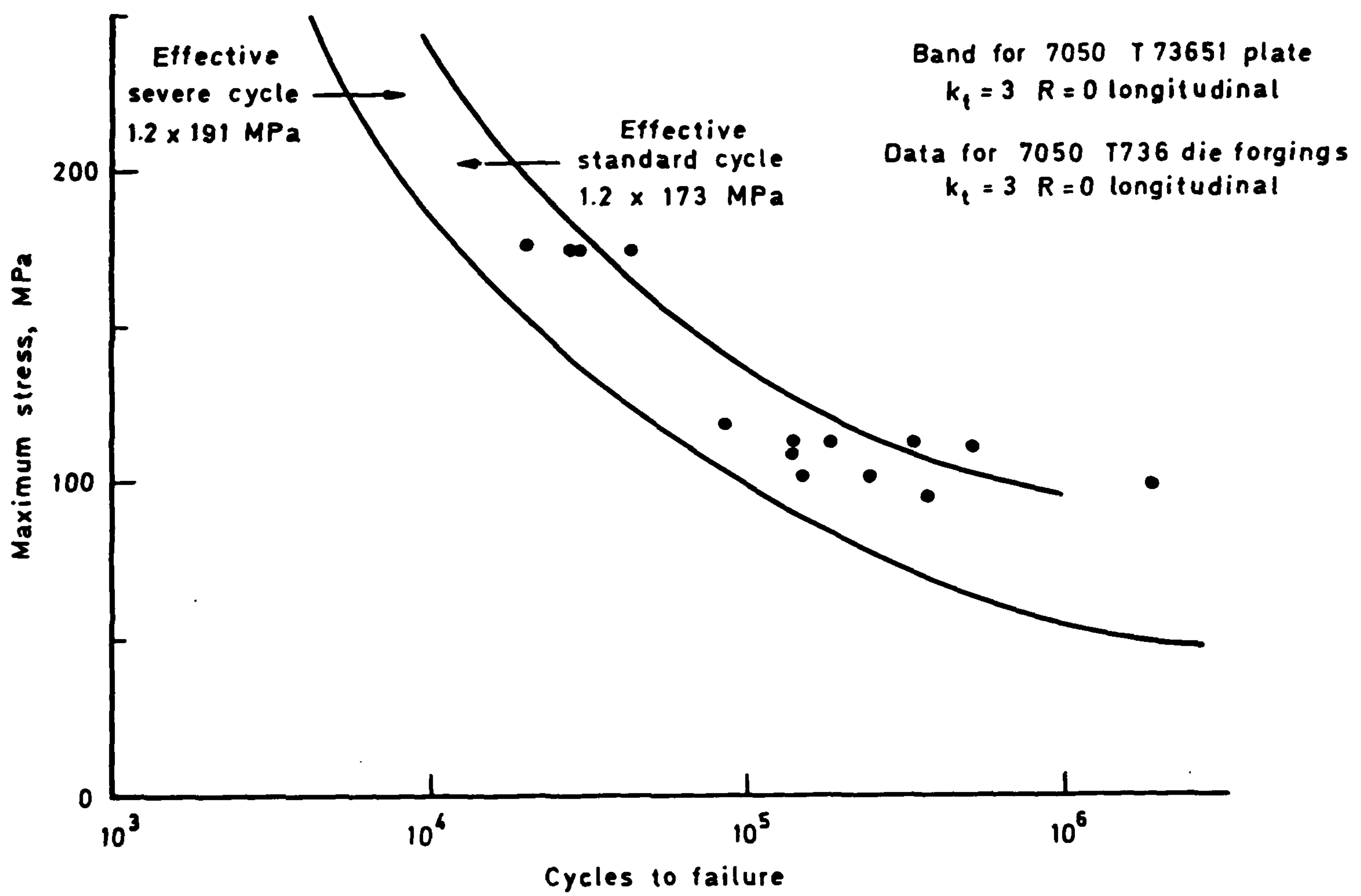

Fig 15 Axial stress fatigue data for 7050 alloy plate and die forgings, showing the levels of effective stress for the severe and standard duty cycles

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17. Abstract

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It was found that the fatigue cracks initiated at a change in section with a poorly machined finish. A fracture mechanics analysis of the striation spacing growth rates close to the change in section indicated that the rough machining effectively increased the K_t of the change in section from 1.7 to nearly 5, producing premature crack initiation and a short fatigue life.

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